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Performance of a wideband multilayer polarizer for soft x rays

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Performance of a Ru/C multilayer polarizer of double-crystal x-ray monochromator type has been evaluated in the soft x-ray region using synchrotron radiation. The throughput efficiencies for *s*-polarized light were found to be 11.5% at 100 eV and higher than 4% over an energy range of 80–150 eV without higher-order contamination. Its polarizance was higher than 99.0% at 88 eV and more than 94% over a range of 80–110 eV.

I. INTRODUCTION

For experiments using polarized soft x rays (SXR) such as circular dichroism spectroscopy, spin-polarized photoelectron spectroscopy, spectroscopic ellipsometry, etc. in the SXR region, accurate evaluation of state of polarization of light emerging from a monochromator is basically important. In the extreme ultraviolet region, traditionally, reflection polarizers are used.[1] However, such polarizers lose their polarizing power for SXR because of grazing incidence essential to keep a reasonable throughput at these wavelengths. As SXR polarizers multilayer polarizers have been recently made use of, because a large ratio between the reflectances for the *s* and the *p* component can be realized in the vicinity of an angle of incidence of $\sim 45°$. Dhez[2] measured the degree of linear polarization of synchrotron radiation (SR) from the ACO storage ring with a Hf/Si multilayer polarizer at 30.4 nm and with a Nb/Si multilayer polarizer at 15.4 nm. Kimura *et al.*[3] used Ru/Si polarizer and analyzer to determine the state of polarization of SR of 12.8 nm from a grasshopper monochromator on the beamline 11A at the Photon Factory.

These multilayer polarizers have high throughput and polarizance (degree of polarizing power). However, they are effective only for SXR of wavelengths in the immediate vicinity of their respective peak wavelengths at an angle of incidence of $\sim 45°$. This narrow-band property of SXR multilayer polarizers limits their applications. By varying the angle of incidence the throughput wavelength can be changed. However, variation of the angle of incidence causes the direction of reflected beam to change.

To overcome the weak points of a multilayer polarizer, we arranged two multilayer polarizers of the same characteristics in the similar way to a double-crystal x-ray monochromator. The two multilayers are translated by an ultrahigh vacuum (UHV)-compatible stepping motor and simultaneously rotated by means of a cam mechanism in such a way that the direction of the beam transmitted through the double-multilayer polarizer (DMP) remains unchanged.

In the previous work[4] we used Ru/Si multilayer polarizers for the DMP, and evaluated its performance with regard to throughput efficiency and polarizance using SR. The polarizance was higher than 99.5% at 89 and 97 eV by measuring the polarization of the emergent beam using a rotating analyzer mounted with a Ru/Si multilayer polarizer. It was also found that the throughput efficiency for *s*-polarized light was higher than 5% over an energy range of 80–120 eV with a maximum of $\sim 32\%$ at 99 eV.

The polarizance was, however, evaluated at only two energies, 97 and 89 eV, where the multilayer analyzer has a main Bragg and a secondary peak, respectively, in reflectance when fixed at an angle of incidence of 45°. In addition, because of the Si *L*-shell absorption, the throughput was largely suppressed above 100 eV, resulting in a narrow effective range of 80–120 eV for practical use.

In this study we measure throughput of the DMP with respect to *s*- and *p*-polarized SXR of various wavelengths so as to evaluate the polarizance over a wide spectral range. As shown in the next section, if we know the degree of polarization of the incident SXR, we can derive a polarizance from the throughput ratio of the two components. To extend the effective spectral range with practical throughput we employ Ru/C multilayer polarizers, which are free from severe absorption in the 100 eV range.

II. ANALYSIS

A. Polarization of incident SXR

We assume that emergent SXR from a monochromator is elliptically polarized, where ellipticity angle is ϵ and azimuthal angle of the major axis is δ, measured from a plane parallel to the positron orbit. Its intensity measured with a rotating analyzer is expressed as

$$I(\eta)=(I_{\max}-I_{\min})\cos^2(\eta-\delta)+I_{\min}, \tag{1}$$

where $I_{\max}$ and $I_{\min}$ are a maximum and a minimum intensity, respectively, and η is the azimuthal angle of the rotating analyzer. $I_{\max}$, $I_{\min}$, and δ are determined by fit-

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ting Eq. (1) to the measured data by a least-squares method. The intensity ratio I_{min}/I_{max} is expressed in terms of ϵ as

$$\frac{I_{min}}{I_{max}}=\frac{r_s \tan^2 \epsilon + r_p}{r_s + r_p \tan^2 \epsilon}, \tag{2}$$

where r is the reflectance of the analyzer, and the subscripts s and p stand for the s and the p component referred to the analyzer. From the values of I_{max} and I_{min} thus determined we can estimate the value of $\tan^2 \epsilon$ if we know polarizance of the rotating analyzer, $(r_s - r_p)/(r_s + r_p)$.

B. Polarization of SXR transmitted through the DMP

When the emergent SXR from a monochromator is viewed from the DMP, where azimuthal angle of its transmission axis is χ, intensity ratio of the p to the s component defined with reference to the plane of incidence is given by

$$\frac{I_p}{I_s}=\frac{1-\cos 2(\chi-\delta) \cos 2\epsilon}{1+\cos 2(\chi-\delta) \cos 2\epsilon}. \tag{3}$$

Then relative throughput for $\chi = 0°$ and 90° is expressed as

$$I_{\chi=0}=R_s(1+\cos 2\delta \cos 2\epsilon) + R_p(1-\cos 2\delta \cos 2\epsilon), \tag{4}$$

$$I_{\chi=90}=R_s(1-\cos 2\delta \cos 2\epsilon) + R_p(1+\cos 2\delta \cos 2\epsilon), \tag{5}$$

where R is the reflectance of the DMP and the subscripts s and p stand for the s and the p component. From Eqs. (4) and (5) we obtain throughput ratio of the two azimuthal angles of the DMP

$$T=\frac{I_{\chi=90}}{I_{\chi=0}} =\frac{R_s(1-\cos 2\delta \cos 2\epsilon)+R_p(1+\cos 2\delta \cos 2\epsilon)}{R_s(1+\cos 2\delta \cos 2\epsilon)+R_p(1-\cos 2\delta \cos 2\epsilon)}. \tag{6}$$

In general, $R_p/R_s \ll 1$. If the incident SXR is almost linearly polarized in a plane parallel to the positron orbit, that is, $\tan \epsilon \ll 1$ and $\delta \cong 0$, the throughput ratio is expressed as

$$T=\tan^2 \epsilon + \frac{R_p}{R_s}. \tag{7}$$

The first term is the intensity ratio of the p to the s component of the incident SXR. If we know the degree of polarization of incident SXR over an energy range under investigation, we can obtain R_p/R_s from Eq. (7) and then polarizance of the DMP, $(R_s - R_p)/(R_s + R_p)$.

III. EXPERIMENT

A 21-layer Ru/C multilayer was fabricated on a silicon wafer substrate by magnetron sputtering. It was cut into two 20×20 mm^2 pieces for use in the DMP. Their peak reflectance was 34% for s-polarized SXR of 99 eV at an angle of incidence of 45°.

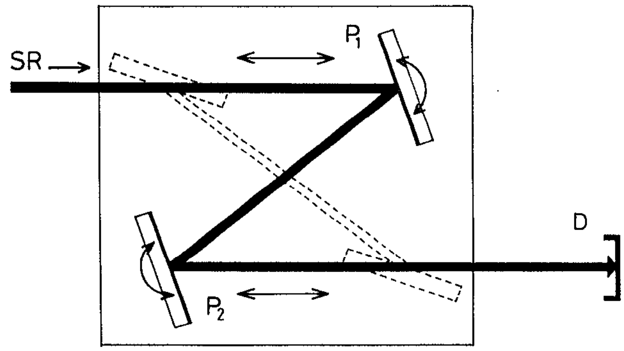

FIG. 1. Schematic diagram of the double-multilayer polarizer and the experimental setup for the evaluation of its performance. P_1 and P_2, multilayer polarizers; D, detector for measuring the throughput of the DMP.

A schematic of the DMP and the experimental setup is illustrated in Fig. 1, where P_1 and P_2 are the Ru/C multilayer polarizers and D is a Ga–As–P photodiode for measuring the throughput intensity. The photodiode has a 10×10 mm^2 detection area, and was examined to be uniform within $\pm 2\%$ in sensitivity.

The performance of the DMP was evaluated using SXR emerging from a 2 m grasshopper monochromator on the beamline 11A at the Photon Factory. The beam size of the incident SXR was ~4 mm (horizontal) × ~2 mm (vertical) at the DMP, leading to no loss of beam due to the dimension of the polarizers.

The state of polarization of the emergent SXR was evaluated by using a rotating analyzer mounted with a Ru/Si multilayer polarizer, whose polarizance is 97% at an angle of incidence of 45° for SXR of 89 and 97 eV.[4] It was found that $\tan^2 \epsilon = 0.010$ (± 0.001) and $\delta \cong 0$ for emergent SXR of 97 eV.

To evaluate throughput of the DMP, first, intensity of the direct beam from the monochromator was measured between 70 and 180 eV with the detector D while monitoring the beam intensity by measuring photoelectric current from a gold mesh placed upstream in the beam path. Next, intensity of SXR transmitted through the DMP for various angles of incidence was measured in the same spectral range for $\chi = 0°$. The throughput was then calculated for the respective angles of incidence. To estimate the polarizance, throughput of the DMP for $\chi = 90°$ was also measured in the same manner.

IV. RESULTS AND DISCUSSION

Figures 2 and 3 show the measured throughput of the DMP when azimuth of its transmission axis is 0° and 90°, respectively. The dashed curves show the throughput at various angles of incidence indicated in the figures. The measured throughput for s-polarized light (Fig. 2) was higher than 4% (5%) over a range of 80–150 eV (84–140 eV) with a maximum of ~11.5% at 100 eV, which is almost consistent with the value of ~11.6% expected from the reflectance of P_1 and P_2. The maximum throughput is, however, lower than that of the Ru/Si DMP, practical throughput ranges over a wider energy region.

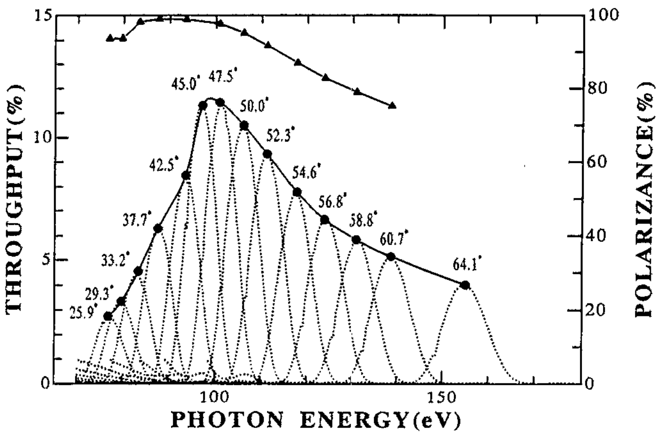

FIG. 2. Measured throughput of the Ru/C double-multilayer polarizer for *s*-polarized light as a function of photon energy. The dashed curves are the throughput at fixed angles of incidence indicated in the figure. The measured polarizances of the DMP are also plotted with ▲.

To examine the characteristic of the higher-order suppression of the DMP, we also measured throughput of the DMP by scanning over a wide range including twice the first Bragg peak energies at several angles of incidence. Absolutely no throughput was observed between 160 and 300 eV, leading to the conclusion that the emergent light from the DMP does not include any higher-order component between 80 and 150 eV. The DMP provides fairly high filtering power. The results of the throughput measurements suggest promising applications of the DMP to the future instrumentation in SXR beamline such as post-focusing mirrors.

By assuming that the state of polarization does not change over the spectral range under investigation, that is, the ratio of intensities along the two elliptic axes of the incident SXR is 0.010 in the 80–150 eV range, polarizance of the DMP is calculated using the measured throughputs for the respective energies. They are summarized in Table I. The polarizance is also plotted in Fig. 2 with solid triangles. The polarizance is higher than 94% between 80 and 110 eV, with a maximum of 99.0% at ~88 eV for an angle of incidence of 40°. It is consistent with a result of simulation that the maximum polarizance occurs at an angle of incidence of ~40° rather than 45°.

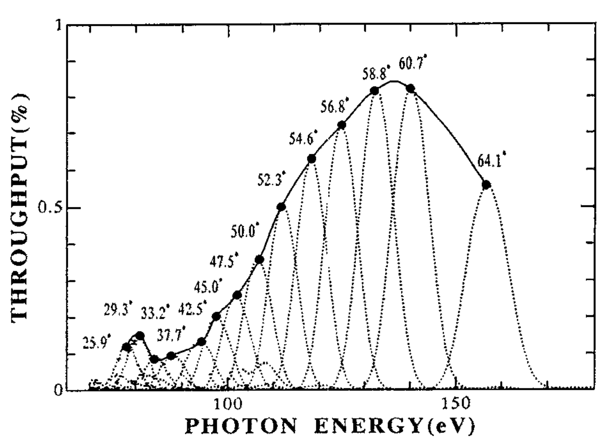

FIG. 3. Measured throughput of the Ru/C double-multilayer polarizer for *p*-polarized light as a function of photon energy. The dashed curves are the throughput at fixed angles of incidence indicated in the figure.

TABLE I. Measured throughput for *s*- and *p*-polarized light and estimated polarizance of the Ru/C double-multilayer polarizer.

Angle of incidence	Peak energy (eV)	Throughput for *s*-polarized light (%)	Throughput for *p*-polarized light (%)	Polarizance (%)
25.9°	76.9	2.74	0.115	93.8
29.3°	79.8	3.38	0.142	93.8
33.2°	83.4	4.46	0.084	98.2
37.7°	87.6	6.30	0.095	99.0
42.5°	93.6	8.46	0.132	98.9
45.0°	97.1	11.32	0.197	98.5
47.5°	100.8	11.43	0.248	97.7
50.0°	106.1	10.49	0.356	95.3
52.3°	111.2	9.33	0.491	91.8
54.6°	117.8	7.78	0.622	87.0
56.8°	123.8	6.65	0.693	82.8
58.8°	131.0	5.85	0.744	79.1
60.7°	138.7	5.15	0.776	75.3

Using the very highly polarized SXR generated by the DMP, studies on optical constants determined from reflectance measurements are now under way.

V. SUMMARY

A Ru/C double-multilayer polarizer has been designed, fabricated, and tested with SR. Preliminary results obtained for SXR of 80–150 eV show that the polarizer provides throughput of >4% with a maximum of ~11.5% at 100 eV without higher-order contamination and that its polarizance is higher than 99.0% at 88 eV and more than 94% over a range of 80–110 eV.

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